PERIODICA POLYTECHNICA SER. CIVIL ENG. VOL. 38, NO. 3, PP. 289–302 (1994)

MIXING OF POLLUTANTS IN RIVERS

Ödön STAROSOLSZKY

Department of Water Management
Technical University of Budapest
Water Resources Research Centre
H–1095 Budapest, Hungary

Received: March 31, 1994

Abstract

Mixing is understood as a basically physical process which is controlled by the properties of the substances involved in it. The various mixing processes in nature can broadly be grouped according to the substances (solid, fluid, gaseous). As a consequence of human activities growing quantities of pollutants can be observed which alerted international organizations. The investigation of the mixing on physical models is rather complicated due to the fact that similarity can only be achieved by using undistorted models. Reliable dispersion coefficients can be expected from the field studies. Methodology and results are demonstrated by measurements over a long Danube reach and within a city. Importance of field studies and the need of further investigations are underlined and the expected results of potential field surveys are summarized. Suggestions for international collaborations are submitted.

Keywords: modelling of mixing, diffusion and dispersion, river pollution.

The Mixing Process

Mixing is understood as the physical process (STAROSOLSZKY, 1986) which takes place in rivers, lakes, the seas and in the groundwater alike and in the course of which water particles of different properties intermingle and transfer mutually their properties. Consequently, at the termination of the mixing process the water particles of different origins and properties amalgamate into a uniform fluid.

The three fundamental processes predominating in natural mixing phenomena are diffusion, turbulent diffusion (MUSZKALAY, 1979) and convection (MUSZKALAY and STAROSOLSZKY, 1985): In fact, the three processes are superimposed on each other, appear simultaneously, but play different roles, the relative importance of which depends on the conditions prevailing in a particular water body.

The phenomenon of mixing is controlled by the physical properties of the substances involved in it, thus by their specific gravity, or temperature, their susceptibility to enter into chemical reactions, solubility and precipitation, settling and suspension, thus factors which may promote and accelerate, or conversely impede and retard mixing.

Depending on their basic property, the waters encountered in nature are classified according to the concentration of the salts they contain as fresh and saltwater.

The counterpart phenomenon to mixing is stratification, in which layers having different properties tend to form in the fluid. These layers are either separated from each other by a sharp boundary, or there is a gradual transition between them. The importance of mixing along these interfaces is attributable to the fact that the living organisms tolerate poorly abrupt temporal and/or spatial changes in water quality.

The various mixing processes in nature can broadly be grouped into three basic forms, such as

- mixing of small solid or gaseous particles present in the water,
- mixing of water particles having different temperatures,
- mixing of water bodies containing dissolved substances in different concentrations.

Substances are termed conservative, if their particles do not react with each other, so that no chemical reaction takes place in the course of mixing, if they retain their material properties so that their concentration alone is changed.

Since natural waters always contain both solid particles and dissolved substances, the possibility must be taken into account that these react with each other, enter into adhesion bonds, or coagulate, or conversely that the solid and gaseous substances become dissolved.

As a consequence of human activities growing quantities of alien substances which may also be classified as pollutants find access to the waters in the form of concentrated, diffuse or linear, further permanent and periodic discharges. The mostly heterogeneous pollution becomes thus a property of the entire water body by the mixing process and affects by dilution the properties of a growing water mass.

Whereas the level of pollution caused by the various pollutants is unlimited , the assimilating capacity of the waters is capable of coping with only a part of them. In keeping with the principle of the conservation of mass, these substances become in some way part of the hydrological cycle, they may separate therefrom (by settling or adsorption) in the course of spreading and turn into hazardous waste which may cause grave concerns over long periods of time. Growing awareness of the environmental problems, a variety of preventive measures, such as multi-stage treatment of industrial and domestic wastewaters, may contribute to controlling the transport processes, but mixing and dilution will still play important roles.

Discharges of even adequately treated wastewaters present still a source of hazards, since unexpected defects or the treatment technology may result in pollution emergencies. Thus a certain risk is associated also with the advanced treatment technologies used in the developed countries emphasizing the importance of mixing in cases of emergency. In such unforeseen pollution accidents the course of events and the consequences thereof cannot be predicted unless the phenomenon of mixing under natural conditions is understood. Such understanding is essential also in devising measures to promote mixing artificially, or to remove the pollutants from the water.

An understanding of mixing phenomena is needed also in estimating the magnitude of the potential losses caused by polluting discharges, just as in formulating the legislative, regulatory, but also the engineering preventive and control measures of coping with the various pollution emergencies.

The issue assumes added importance where the possibility of transboundary pollution exists. Most major streams, lakes and seas but even groundwater aquifers extend across boundaries. The growing problems associated with transboundary pollution are addressed also by several international organizations. Important progress in this domain has been made at the UN Economic Commission for Europe, where a code of practice has been adopted on transboundary pollution accidents (UN-ECE, 1989). Under the impact of the Tshernobil disaster, the hydrologic implications of water pollution have been studied also in the Commission for Hydrology, World Meteorological Organization, where directives applying to surface- and groundwaters alike have been compiled (WMO, 1992).

Advance in Mixing Theories and Applications

Prompted by the foregoing, the professional literature on mixing has multiplied over the recent 20 years and the related issues have been addressed at a number of national and international scientific events (e. g. the ASCE, and the IAHR). Thanks to the advances achieved during the past two decades,

(*i*) the theoretical approaches to describing the mixing process analytically have been cleared in many respects,
(*ii*) solutions have been developed for the numerical solution of the equations under known conditions (GÁSPÁR and JÓZSA, 1991) and
(*iii*) for simpler cases (e. g. single- and two-dimensional steady flow) verified results have been presented.

The solutions depend for their reliability and accuracy mainly on the numerical parameters. However, the dispersion and diffusion coefficients are still assumed with the help of empirical formulae which are of questionable reliability in particular cases. This means that while the analytical methods have attained a high level of sophistication, the parameters, numerical quantities involved in their application are still obtained by rather crude approximations.

Consequently, problems are still encountered in any attempt at a quantified description of actual mixing processes in surface- and groundwaters alike.

Physical Modelling of Mixing

Physical modelling which has produced results of practical interest in the case of flow phenomena is mush more difficult to apply to such of mixing (STAROSOLSZKY, 1970).

Attention should be called to the fact that the distorted models commonly applied in river hydraulics are unsuited to any quantified study of dispersion phenomena.

This is demonstrated by writing the differential equation of the conservation of material in the form

$$\left[\frac{u_o L_o}{D_o}\right]\left(\frac{\partial \overline{c}}{\partial t}+\overline{u}\frac{\partial \overline{c}}{\partial \overline{x}}\right)=\frac{1}{\overline{F}}\frac{\partial}{\partial \overline{x}}\left(\overline{FD}\frac{\partial \overline{c}}{\partial \overline{x}}\right), \tag{1}$$

where u is the velocity of flow, L the typical dimension , F the cross-sectional area, c the pollutant concentration, D the diffusion coefficient, t the time and x the distance in the direction of flow. The subscript o refers to the reference datum, while the overhead dash indicates in this case a dimensionless value of the typical quantity divided by the reference datum (e. g. $x = x/L_o$, $u = u/u_o$ etc).

Quite obviously, for the model and the prototype to be similar the dispersion Reynolds number, $u_o/L_o/D_o$ must equal unity, i. e.,

$$\frac{\lambda_u \lambda_L}{\lambda_D}=1, \tag{2}$$

where λ is the ratio of the quantities indicated by the subscript. In river models the law of Froude must be satisfied, thus

$$\lambda_u=\lambda_y^{\frac{1}{2}}, \tag{3}$$

where λ_y is the vertical scale ratio.

Calculating the conversion factor of the dispersion coefficient by the formula $D = ARu$ proposed by ELDER (1959), where R is the hydraulic radius and u the shear velocity:

$$\lambda_D = \lambda_R \lambda_u = \lambda_y \lambda_u \,, \tag{4}$$

then

$$\frac{\lambda_y^{\frac{1}{2}} \lambda_L}{\lambda_y \lambda_y^{\frac{1}{2}}} = 1 \,. \tag{5}$$

The equation is invalid, unless $\lambda_L = \lambda_y$, i. e. the model is an undistorted one. A similar result is obtained if the dispersion coefficient is calculated with the help of the formula proposed by FISCHER (1967).

This relationship should be remembered when using hydraulic models to the study of river regulation problems involving dispersion processes as well.

Diffusion and Dispersion Phenomena in Natural Channels

The sphere of conventional river regulation objectives has expanded recently, especially in the densely populated and industrialized regions, by such which had little importance in the past. These are related to the discharges of wastewaters into the rivers and include the following requirements:

a) The discharges introduced should be mixed thoroughly over the shortest possible distance and time.
b) The harmful pollutants should decompose at the fastest possible rate.
c) The solids introduced should be prevented from settling and from forming a blanket floating on the surface.
d) Conditions should be prevented under which foaming agents are induced to create large masses of floating foam.

Considerable difficulties are often encountered in trying to satisfy the conventional and more recent requirements simultaneously.

Mixing and decomposition can be encouraged on the one hand by appropriately designed outfall structures (called also diffusers), on the other by locating them in a way to make the fullest possible use of turbulent diffusion.

In cases where the natural channels offer no suitable discharge opportunities, it may become necessary to resort to river training works to create these. Changed diffusion processes should be taken into account,

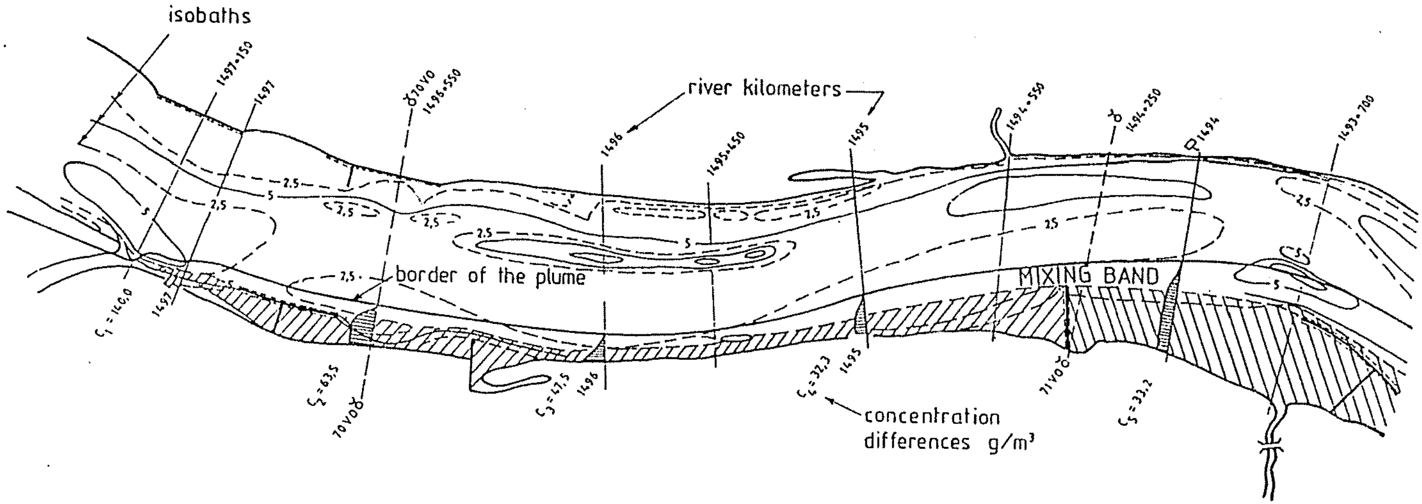

Fig. 1. Concentration rises in the dead spaces between spur-dykes due to accumulation of contamination originated from a tributary (River Danube)

evidently, also in designing intakes and in deciding on the lowest flow to be retained in the river, since these processes change normally in a non-linear manner as the river flow is reduced. Over backwater reaches the reduced flow velocities may induce adverse changes, the prediction of which is a prerequisite to taking the appropriate remedial measures.

Tributary inflows tend, sometimes, to be separated from the recipient and their plumes can be observed in a longer distance.

Pollution sources can easily be detected. While the mixing in verticals place rather soon, mixing in transversal direction may take several kilometers.

The effect of river training works, forming dead spaces for the flow, can be very characteristic. In these dead areas the total concentration of the salts can be higher than in the recipient or in the plume of the tributary, as it was found in a Danube reach (*Fig. 1*).

Settling of the pollutants introduced had adverse consequences in Hungary, too, in that the increased resistance of the soil filter has decreased the yield of bank filtered water wells.

In order to prevent settling it may be necessary to subject the wastewater to treatment (settling out the solids) prior to discharging it. Any rapids, or structure is liable to induce foaming which is therefore very difficult to prevent.

Mixing is the principal phenomenon by which the impacts of thermal pollution can be mitigated.

In selecting a particular method of river regulation these considerations should always be remembered (STAROSOLSZKY, 1980), even if solutions meeting all requirements are difficult to find, and the special laws applying to the flow of multi-phase fluids containing not only natural sediments should be introduced.

The Method Surveying Mixing Processes

More reliable dispersion coefficients can hereafter be expected from results observed in the course of field studies. These may involve the use of tracers, the dispersion coefficient being calculated from the distribution of the labelled particles in the plume or cloud. Changes in salts concentration, provided these can be measured at actual discharges or at the entrance of tributaries, may be used as natural tracer in such field studies. Examples of this method have been described in several papers by MUSZKALAY and STAROSOLSZKY (1987a, 1988, 1989.)

Survey of Mixing Conditions

Effluent discharges cause plume- or jet-like concentration distributions in streams. Conventional sampling studies are extremely laborious and expensive, especially on major streams. The samples take a long time to analyze and the data to process, especially where a river stretch, rather than a single cross-section, and several outlets simultaneously, are studied.

A method of surveying and data processing has been developed (MUSZKALAY and STAROSOLSZKY, 1987a) which is capable of providing in a short time a picture about effluent mixing, of describing dilution and makes, thus, improved outfall designs, modeling the river reach and studying effects of hydraulic structures possible.

The principle underlying the survey consists of recording the dissolved salt content through electric conductivity by cross-sections or along the stream profile. Conductivity is measured by means of an a. c. powered carbon electrode and a working resistor, the electric signal proportionate to the conductivity of water being produced on the latter. After rectification the electric signal is registered continuously with a rapid recorder. The correlation between the electric conductivity and the dissolved salt content of normal composition is found by calibration tests, on the basis of which the dissolved salt content, as well as the spatial and temporal variations thereof can be determined from the record.

For the survey a probe is towed by a launch along the selected cross-sections or profiles at a uniform velocity not higher than 1.5 m/s, recording the electric signal continuously. Unless the differences along depth are not wide, the towing depth of the probe may be from 0.5 to 1.0 m.

Parallel to recording the electric conductivity the cross-sections are surveyed — unless the results of earlier topographic surveys are available — the vertical distribution is determined at the discharge site, the data on the effluent discharged are collected and the streamflow rate in the discharge cross-section is measured by means of a revolving current meter. In the case of effluent discharges conductivity surveys are run in the discharge cross-section, in one situated upstream therefrom at a distance equal to the surface width and in three to ten cross-sections along the plume depending on the rate of concentration change. It may be advisable to run surveys along the stream between discharge points to detect any effects in the profile.

Data Processing

Concentrations can be calculated and represented by cross-sections from the records. The distribution of flow rates should also be found within the cross-sections. Based on the principle of conservation of matter and assuming steady water- and pollutant flows, the water and salt discharges calculated from the summed partial streamflows and salt concentrations should thereafter be checked for agreement. According to experience, over stretches without discharges both the streamflows and the salt transport rates should agree to within 5%. Any deviations should be corrected to the average salt transport rates by modifying the concentrations proportionately.

The excess concentrations measured in the plumes should be determined relative to the background concentration in the recipient stream. By plotting the concentration peaks in a log-log system against distance, it becomes possible to estimate the transversal mixing coefficient D_y in the recipient, or the distance at which the effluent is spread in the entire cross-section.

In a map showing the differences in concentration it is advisable to trace the line connecting the peak values, i. e., the path along which the plume progresses, as well as the lines connecting the detectable edges of the plume, i. e., the diagram of plume spreading. The lines connecting the locations of equal concentration can also be plotted, resulting in a map of isohalinity.

Opportunities where the flows of tributaries or the discharges from sewers can be observed over longer sections are especially valuable. Obviously, the effects of mixing are most pronounced at times of low water, where the salts concentration in the discharge differs appreciably from that of the recipient, or where the entering discharge is significant relative to the recipient flow.

Observations over long river reaches allow the identification of section characteristics and the detection of their variability (MUSZKALAY and STAROSOLSZKY, 1991), while along section in towns the detection of overlapping plumes as well (MUSZKALAY and STAROSOLSZKY, 1987b).

Mixing Over Longer Reaches

Over the 208 km long Danube section between Rajka and Budapest conductivity records were taken in four series with several overlaps in 298 cross-sections and along 60 longitudinal part profiles. The total number of recordings was 389 (or 472 including the preparatory measurements) corresponding to 0.535 (0.441) cross-sections studied per kilometer. The measurements were performed in four series between September, 1987 and March, 1988.

The stream sections considered uniform as regards hydraulics and mixing conditions were selected from these and the Danube section studied (including the Moson Danube) was subdivided hereafter into 44 reaches by averaging the reach parameters and with regard to the discharge points.

Following some corrections to the measurement data these may be considered free of the effects of variations over time. These concentration data have been plotted to a logarithmic scale similar to *Fig. 2a,* indicating also the parameters of the 28 major discharges, the streamflow rates and the mean concentrations over the reaches.

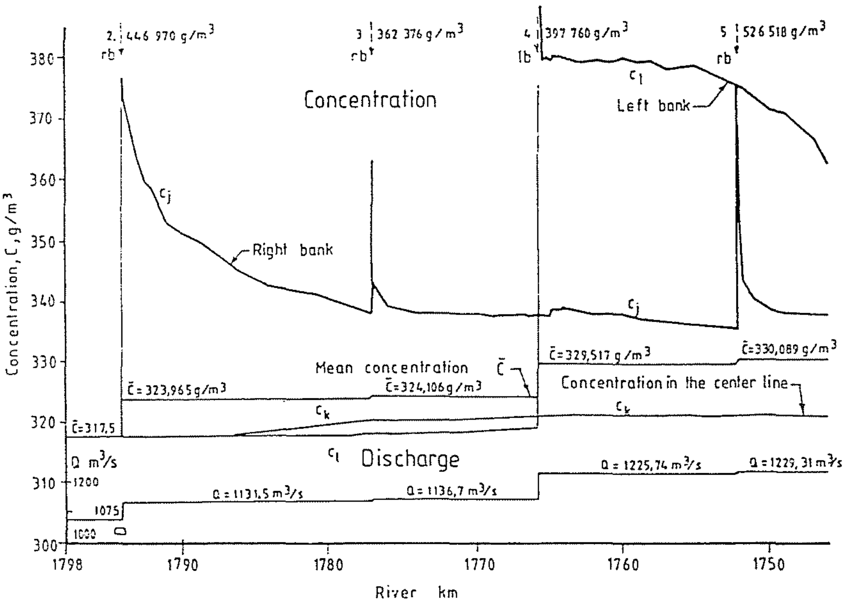

Fig. 2. Variations in the concentration measured along the Danube reach considered

From the analysis of concentrations along the section the following conclusions may be arrived at. The Danube arrives at the national boundary with a higher concentration along the left-hand bank, but upstream thereof the plume has attained the right-hand bank, implying that the first mixing length of an upstream tributary is situated between the sources and the national boundary. The concentration increment relative to the reference value considered upstream from the confluence of this tributary in 25.55 g/m^2 along the left hand bank and 8.48 g/m^2 along the right hand bank. Complete mixing occurs between river stations 1810 and 1800 km, where the differences in concentration along the cross-section remain below the threshold of measurement.

On the right-hand bank, downstream of the confluence of the Moson Danube the concentration level rises steeply to decrease hyperbolically farther downstream. The material discharged by the two largest tributaries, the Moson Danube and the Vág Danube do not mix completely in the recipient down to the tip of Szentendre Island (R. St. 1691 km). The influence of the Vág Danube remains predominant along the left-hand bank in the Vác Danube arm. The left-hand bank values in the Vác Danube arm and the right-hand bank data in the Szentendre Danube arm are shown in the longitudinal profile, in which the discharge points appear as steep changes in concentration.

Mixing within Cities

The metropolitan area of the Danube from 1657.5 rkm to 1642.5 rkm over a 15 km long reach was investigated on 07.10.1986 when the mean discharge of the Danube was 1030 m^3/s and the average concentration upstream of Budapest was 360 g/m^3. The survey was made between two major islands of the Danube, from the southern tip of the Szentendre Island to the northern tip of the Csepel Island, where a barrage closes an old Danube arm supplied by an intake structure, like a diversion.

Over the investigated reach 11 outfalls increase the unevenness of the concentration distribution (*Fig. 9*). The maximum concentration could be observed along the left bank of the river which may cause higher concentration in the diverted water. 5 outfalls are of waste water and 6 are of natural origin, but slightly polluted.

The 11 outfalls increase the discharge by 22.5 m^3/s characterized by 1420 g/m^3 concentration. Due to the pollution load 11 plumes were detected.

The calculated dispersion coefficients were between 0.1 and 0.3 m^2/s, and due to the outfalls the concentration peaks could be observed along the banks, and the concentration is the lowest in the drift. The plume of outfall Nr. 10 can be more effective in higher discharges, in particular due to the higher turbulent diffusion caused by the pier of a bridge. The dilution of the plume from outlet Nr. 1 is relatively low and dispersion coefficient is only 0.04 m^2/s, therefore it can be detected over a stretch of 8 km.

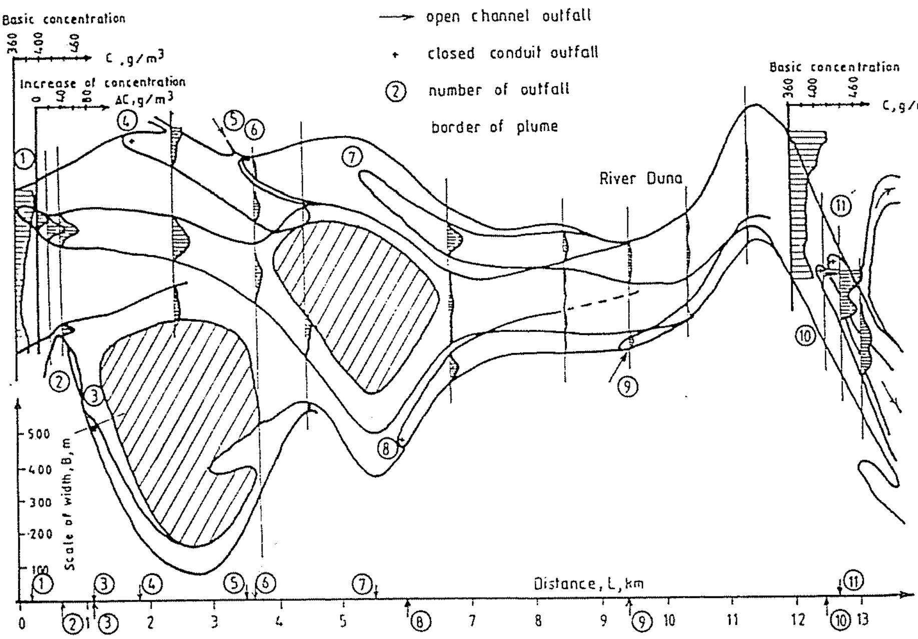

Fig. 3. Lay-out of the Budapest Danube reach with plumes and concentration distributions

Need of Further Studies

In the previous chapters an attempt has been made to demonstrate the recent status of our knowledge on mixing conditions. The major difficulties in our efforts to describe real conditions are listed as follows:

- Theoretically the transport equations, at least in their tri-dimensional forms, may characterize the mixing conditions, however, in the practice the necessary data are either completely missing or they are scarce to feed the more complicated models.
- The two dimensional (vertical averaged) treatment is insufficient in meandering alluvial rivers or in mountainous streams where tri-dimensionality of the flow may generate completely different conditions.
- The parameters for a numerical solution either need rather tedious field measurements or rough estimations can only be accepted.
- The scaling of physical models to investigate mixing conditions and the generation of lateral velocity distribution similar to the natural one, are extremely difficult.
- There is a rather great uncertainty in the application of steady diffusion-dispersion coefficients in alluvial streams.

- Trace experiments on large rivers need an enormous amount of tracer material. The natural tributaries or artificial outfalls can be used as tracers, if the concentrations are easily detectable.
- Mixing conditions may change according to the flow. Thus, the variation of the dispersion/diffusion coefficients as a function of discharge (or water stage) should also be considered.

Conclusions

A better understanding of mixing phenomena, the quantification of the parameters involved and their application to the operative prediction of pollutant waves would presume organized field studies performed according to uniform principles on the major and especially the international streams. The expected results thereof would include:

(1) the identification of the impacts of tributaries and wastewater discharges from actual observation data,
(2) prediction with the required accuracy of the propagation of actual polluting discharges to the downstream sections of the river,
(3) taking the appropriate engineering measures to improve mixing of discharges,
(4) the possibility of making allowance for mixing in the design of river regulation structures (MUSZKALAY and STAROSOLSZKY, 1988),
(5) the improvement of the numerical methods on the basis of actual observation data.

In the interest of the foregoing, international cooperation is considered necessary, by which

(*a*) the methodology of such studies could be standardized,
(*b*) the circumstances of internationally acceptable observations and the procedures on international rivers could be specified,
(*c*) the coordination of observation in time and as regards sites along the major streams could be initiated,
(*d*) the results could be processed to make them comparable and the accuracy of the present approximate formulae could be improved,
(*e*) the financial burdens of such studies on some countries could be relieved.

References

ELDER, J. W. (1959): The Dispersion of Marked Fluid in Turbulent Shear Flow. *Journal of Fluid Mechanics.*

FISHER, H. B. (1967): The Mechanics of Dispersion in Natural Streams. *Proc. of the ASCE, Journal of the Hydraulics Division,* HY6, Nov.

GÁSPÁR, CS. – JÓZSA, J. (1991): A Coupled Lagrangian Particle Tracing and Quadtree-Based Adaptive Multigrid Method with Application to Shear Layer Evolution. *XXIV. IAHR Congress,* Madrid.

JÓZSA, J. (1989): Modelling Pollution Distibution Irregularities in a River System due to Peak Load Operation of a Water Power Plant. *Proc. XXIII Congress of IAHR,* Ottawa.

LEE, J. H. W. (1985): Comparison of Two River Diffuser Models. *Journal of Hydr. Engng. ASCE,* Vol. 111. No. 7.

MUSZKALAY, L. (1979): Three-dimensional Turbulence in Streams and its Role in Mixing.*Proc. XVIII. IAHR Congress,* Vol. Ba7. Cagliari.

MUSZKALAY, L. – STAROSOLSZKY, Ö. (1981): New Aspects in the Advance on Fluvial Hydraulics. *Proc. Int. Conf. on Fluvial Hydraulics,* Budapest.

MUSZKALAY, L. – STAROSOLSZKY, Ö. (1985): Two- and Three-dimensional Flow Measurement in Large Rivers. *Proc. XXI IAHR Congress,* Melbourne.

MUSZKALAY, L. – STAROSOLSZKY, Ö. (1987a): Field Study into the Mixing of Effluents in Streams. *Proc. XXII. IAHR Congress,* Lausanne.

MUSZKALAY, L. – STAROSOLSZKY, Ö. (1987b): Impact of Multiple Outfalls on River Reaches within Cities. Int. Symp. on New Technology, Pune.

MUSZKALAY, L. – STAROSOLSZKY, Ö. (1989): Characterization of the Mixing Conditions in a Stream. *Proc. XXIII. IAHR Congress.* D 301, Ottawa.

MUSZKALAY, L. – STAROSOLSZKY, Ö. (1991): Study of Mixing Conditions along the Hungarian Danube upstream of Budapest. IAHS Symp.H3. XX General Assembly of IUGG. *Mitteilungsblatt des Hydrographischen Dienstes in Österreich.* Nr. 65/6. Wien.

STAROSOLSZKY, Ö. (1970): Considerations on Scale Modelling of Diffusion and Ice Phenomena (in Hungarian). *Hidrológiai Közlöny,* 1970/1, Budapest.

STAROSOLSZKY, Ö. (1980): Aspects of River Training and Pollution. *Int. Symp. on River Development,* Belgrade.

STAROSOLSZKY, Ö. (1986): Applied Surface Hydrology 2–4. Transport Flow Phenomena. *Water Resources Publications,* Littleton, Col.

UN-ECE (1989): Draft Code of Conduct on Accidental Pollution of Transboundary Inland Water, Geneva.

WMO (1992): Hydrological Aspects of Accidental Pollution of Water Bodies. Operational Hydrology Report No 37. Geneva.